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RESEARCH IN THE DEVELOPMENT OF THIN-FILM DEVICES
AND IN THE STUDY OF DEVICE PHYSICS FOR OPTICAL
COMMUNICATIONS AND OPTICAL ELECTRONICS

FINAL REPORT

S. WANG

15 November 1973 - 14 November 1979

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ELECTRONICS RESEARCH LABORATORY
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19. ABSTRACT (Continue on reverse side if necessary and identify by block number) Our research effort is reviewed in four basic areas: (1) experimenting with new laser structures for providing two-dimensional waveguiding to control lateral modes, (2) investigating suitable waveguiding structures for use as the building block for future monolithic integration of optical components based on GaAs technology, (3) developing technologies related to material aspects for GaAs and related semiconductors, such as oxide formation and LPE growth of quaternary compounds, and (4) studying and demonstrating the (continued on back)		

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use of Ti-diffused LiNbO₃ waveguides in integrated-optics applications as modulators and power dividers. Using LPE growth over chemically etched channels we have developed new lasers with two-dimensional waveguides to stabilize the lateral modes. These lasers show linear light versus current relation, stable radiation pattern, and single mode operation up to 2 J_{LH} capable of delivering 70 mW power. Using a waveguide structure containing a large optical cavity (LOC), we have been able to integrate a DBR laser with a detector and with a modulator. The LOC scheme enables us to remove the GaAs layer from the passive region, which in turn makes possible the attainment of high differential quantum efficiency in the DBR laser and also the use of the same structure as the building blocks for monolithic integration. The fabrication requires only a one-step LPE growth. As a preparation for future work, preliminary experiments on anodic oxidation of GaAs, high temperature effects in LPE layers grown on GaAs wafers, and LPE growth of (GaIn)(AsP) layers have been initiated to gain experience and insight as to the problems involved. For LiNbO₃ work, we have tried Ti diffusion in Li₂O atmosphere to suppress Li₂O out-diffusion and successfully made two-dimensional waveguides with elimination of unwanted surface waveguides. Electrooptic modulators and dividers with a modulating voltage in the neighborhood of 4 volts have been demonstrated.

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I. REVIEWS OF ACCOMPLISHMENTS (A Final Report) AND BACKGROUND DISCUSSION FOR FUTURE RESEARCH

During the past two and one half years, we have steadily built up our experimental capability in semiconductor-laser and integrated-optics research. Our objective was to develop active and passive components for optical guided-wave communication systems. The materials used in the investigation are compound semiconductors GaAs and (GaAl)As for lasers and ferroelectric LiNbO₃ for electrooptic modulators. Our research effort consisted of (1) experimenting with new laser structures for providing two-dimensional waveguiding to control lateral modes, (2) investigating suitable waveguiding structures for use as the building block for future monolithic integration of optical components based on GaAs technology, and (3) studying the potential use of Ti-diffused waveguides in LiNbO₃ for integrated-optics applications. As preparation for future research, we also worked on semi-insulating GaAs, studied the process of anodic oxidation for growing native oxides on GaAs, and started LPE work for growing films of quaternary compounds (GaIn)(AsP) on InP substrates.

In the area of lateral-mode control, we used the technique of LPE growth over etched channels⁵⁻⁷ to fabricate laser structures which provide waveguiding in the lateral direction (parallel to the junction) as well as in the transverse (thickness) direction. An etched channel by nature has two types of corners: convex at the top and concave at the bottom. During LPE growth, the melt has different enthalpy at these corners because of difference in the surface energy (or surface tension). As a result, a uniform, saturated melt behaves like an undersaturated one at a convex corner and like an oversaturated one at a concave

corner, causing a slight melt-etch-back at the former and a fast growth at the latter. The differential growth rate results in a thickness variation⁷ of the grown layers in the channel region (with decreasing thickness away from the center). Since the propagation constant in a waveguide increases with waveguide thickness, the resultant thickness variation produces an effective-index difference in the lateral direction which together with the index difference caused by the heterostructure in the transverse direction produces two-dimensional waveguiding. Such a two-dimensional waveguide based on thickness variation supports relatively few modes, and thus is more amenable to single-mode operation, than buried heterostructures of comparable physical dimensions.^{5,6,8}

Using the thickness variation scheme, we built two new laser structures: the IRW (inverted ridge waveguide) laser⁹ and the CJ (curved junction) laser.¹⁰ The IRW laser shows linear light output (free of kink) versus injection current and stable mode pattern (fundamental lateral mode) up to $1.3 J_{th}$. Upon further increase of injection current, multi-filamentary behavior and multi-longitudinal modes begin to appear. These tendencies are caused by a too large effective index variation and by a relatively flat gain profile in the lateral direction. In the CJ laser, an extra $(Ga_{1-x}Al_x)As$ layer with a small $x < 0.1$ was introduced to form a large optical cavity. The separation of the active layer ($GaAs$) from the main waveguiding layer ($Ga_{1-x}Al_xAs$) makes it possible to control the effective index variation and the gain profile separately. The CJ laser has a peaked gain profile and a two-dimensional waveguide supporting only few lateral modes. Because of these improvements, the laser shows linear light output versus injection current and stable fundamental lateral-mode and single longitudinal-mode

operation up to $2 J_{th}$. The characteristics of a typical CJ laser with a 15 μm -wide channel are shown in Fig. 1. A threshold current as low as 120 mA is obtained in CJ lasers with 5 μm channel width.

In the area of integration, we used a waveguide structure containing a large optical cavity (LOC) as the building block. In the passive region (that is, waveguide connecting two electro-optic devices) the GaAs layer is removed to overcome the problem of absorption. In the device region, the GaAs layer is retained either for amplification or for detection of the optical signal. Using the LOC scheme, simple integration of optical components requires only a single-step LPE growth. Post LPE steps, such as chemical etching or diffusion if needed, can be used to fabricate different optical or electro-optic devices, such as the DBR laser or the junction detector.

To demonstrate this possibility, we fabricated LOC waveguiding structures consisting of two tandem device sections separated by a passive section. Gratings were then etched into the passive region to form a DBR laser for one section and to provide optical isolation between the two sections. The two tandem sections thus form laser-detector combination¹¹ when the other section is reverse biased or a laser-amplifier combination¹² when the other section is forward biased. Excellent correlation between the laser output power and the detected current was obtained, and this laser-detector combination should be useful in future optical communication systems; for example, the detected output could be used to monitor and thus to control the laser operation in a feedback control circuit. For the laser-amplifier combination, a maximum ratio of ten was achieved for the depth of modulation. In our preliminary experiment, the devices were of broad dimensions. The achieved depth of

modulation was limited by the available excitation current from the power supply, and not by any adverse effect such as parasitic oscillation. For a LOC waveguide with a confinement factor of 0.1, the reflection coefficient at the two ends of the amplifier section should be less than 0.1, and a maximum power gain of 100 should be possible without causing oscillation in the amplifier section.

The LOC structure is useful not only in integration but also to the DBR laser itself. The differential quantum efficiency of the DFB and DBR laser (typically less than 10% as reported in the literature) was considerably lower than that of the conventional Fabry-Perot laser. Here the absorption in the passive region, the distributed Bragg reflector, is again an important factor. It not only lowers the reflectivity but also broadens the bandwidth of a Bragg reflector. By removing GaAs completely from the DBR region (as evidenced from absence of luminescence from the region), we achieved in the DBR laser a high differential quantum efficiency¹³ (16% from one facet and 32% in total) comparable to that of conventional Fabry-Perot laser. In this laser, we could see clearly the effect of the Bragg reflector even below laser threshold, that is, the spontaneous emission showed characteristic longitudinal mode pattern because of its interaction with the grating. The characteristics of the high efficiency DRB laser as well as the laser-detector and laser-amplifier combinations are shown in Fig. 2.

In the area of electro-optic modulator, our accomplishments were in three main areas: (1) suppression of Li₂O out diffusion during Ti in diffusion, (2) demonstration of branched-waveguide modulator and clarification of the mode behavior at a fork junction, and (3) demonstration of a new detection scheme for Ti:LiNbO₃ waveguides. One serious problem

we faced in making Ti:LiNbO₃ waveguides was out diffusion of Li₂O from LiNbO₃. This out-diffusion produces an unwanted surface waveguide in addition to the desired two-dimensional waveguide. This was evidenced by the presence of broad mode lines (due to the surface waveguide) in contrast to the sharp mode lines of the Ti in-diffused waveguide. We overcame this problem¹⁴ by performing the Ti in-diffusion in a Li₂O atmosphere which maintained a positive Li₂O pressure and thus prevented Li₂O out-diffusion. Using this technique, we were able to fabricate single-mode Ti-diffused waveguide in LiNbO₃ for the He-Ne 1.15 μm wavelength (the reduction camera in our laboratory limited the mask opening to larger than 4 μm).

Insofar as modulator work is concerned, we used both a single fork as a power divider and a two-fork configuration as a Mach-Zehnder interferometer. With the latter we were able to achieve a depth of modulation about 80% with an applied voltage of 4.8 volts.¹⁵ In our study, the mode behavior at a fork was investigated in order to further improve the modulator performance. We find that a fork not only splits or combines the power but also may change the mode order. The latter effect¹⁵ plays an important role in the electro-optic modulator in the Mach-Zehnder configuration. As an integral part of the integrated-optics work, we also studied suitable means for detecting the optical signal. Because LiNbO₃ is an insulator, the function of detection can only be effected by first extracting light using a prism or grating coupler and then imaging the extracted light onto a discrete detector. The scheme we demonstrated¹⁶ utilized an etched mesa Si photodiode in direct contact with a LiNbO₃ waveguide. Extraction of light is through direct evanescent field coupling. Thus the Si diode performs both the

function of extraction and detection. Since the scheme eliminates the need for the intermediary coupling and imaging optics, it should open up possibilities for hybrid integration. To demonstrate this integration possibility, we placed a mesa Si detector in direct contact with one branch of a Ti:LiNbO₃ fork waveguide. When an electric field was applied to the fork region, redistribution of energy into the two branch waveguides produced modulation of the detected signal.¹⁶ A detection efficiency about 60% was achieved, corresponding to a detector sensitivity of 0.6 nA of short-circuit current per 1 nW of waveguide power. The output of the Mach-Zehnder interferometer modulator and that of the branch-waveguide modulator are shown in Figs. 3 and 4, respectively, the former using the conventional detection scheme and the latter using the evanescent coupling scheme.

As preliminary studies in preparation for future research, we also did work on the following subjects: (1) oxygen-implantation in GaAs and LPE growth on Cr-doped semi-insulating GaAs, (2) anodic oxidation of GaAs, and (3) LPE growth of quaternary (GaIn)(AsP) films on InP substrates. Our objectives were to learn and advance the GaAs technology and to extend the established GaAs technology to other III-V compound semiconductors. Besides high electron mobility and useful band structures, GaAs has another distinct advantage over Si in that GaAs can be made semi-insulating by compensation either through deep donors known to be oxygen related centers¹⁷ or through deep acceptors known to be Cr related center.¹⁷ However, many devices of III-V compounds such as FET's and injection lasers require processing of the wafer at high temperatures such as VPE or LPE growth of multi-layer structures. Therefore, the effect of diffusion^{18,19} and annealing on the semi-insulating

layer should be addressed. Another important question related to the GaAs technology is the quality of the oxide of GaAs. Growing high-quality SiO_2 is an essential part of the Si technology. For example, a thermally stable oxide is used for masking and an oxide giving rise to low interface density of states is needed in MOS devices such as the MOSFET. Finally, compound semiconductors other than GaAs deserve attention. The quaternary system (GaIn)(AsP) is an attractive candidate for investigation because of the possibility of lattice match to InP and because it covers the wavelength range for low loss²⁰ and zero dispersion²¹ in optical fibers. Also the quaternary laser has been reported to have a long operating life.²² A brief summary of our activities in the three aforementioned areas is given below.

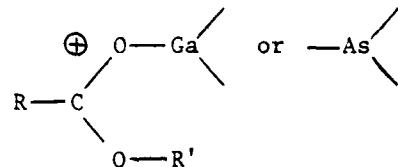
During our laser work, we investigated various ways of confining the injection current to the active region of a laser. One way is to convert the surface of a GaAs wafer by oxygen implantation and then etch a channel through the semi-insulating layer. Upon LPE growth, the laser structure will have its current path confined to the etched channel. A similar scheme was tried at Technical University of Aachen.²³ We used a dosage of 10^{14} cm^{-2} which was limited by the beam current of our implantation machine. A high resistivity layer was established before LPE growth. However, after LPE growth, the laser structure did not show much the effect of current confinement. We believe that the effect of implanted oxygen may have been substantially reduced by either annealing or diffusion.¹⁸ This conclusion is consistent with the reported phenomenon of thermal conversion.²⁴ The importance of high-temperature effects on semi-insulating layers was also manifested in our work on Cr-doped substrates. We tried to grow high-purity (unintentionally

doped) LPE layers on Cr-doped substrates to determine the background impurity in our LPE system for its suitability for GaAs FET work. Electrical measurements (resistance and C-V measurements) on the various structures we made show thickness-dependence of the properties of the grown layers. This dependence could well be due to out diffusion of impurities from the Cr-doped substrates. Since semi-insulating substrates and layers are used in many devices such as FET's and lasers and since processing at high temperatures is required in the fabrication of the devices, further and more extensive study of the thermal effects is warranted such as diffusion of Cr and O dopants and annealing of defects caused by O implantation.

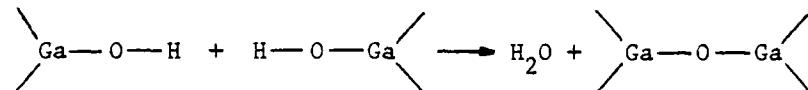
Another subject we undertook to investigate is anodic oxidation of GaAs. There has been considerable interest to establish a technology to form insulators on semiconductor with good interface properties. Many of the properties of the Si-SiO₂ system, which were employed into modern IC technology, do not exist with other semiconductors due to lack of a comparable oxide. The discovery²⁵ and later refinement²⁶⁻²⁸ of a native oxide of GaAs has prompted interest in the development of a comparable system with GaAs. One convenient way of forming an oxide is by anodic oxidation and much of efforts was directed toward finding a suitable anodizing electrolyte. An understanding of the anodic reaction that takes place during oxidation would be beneficial in that it would help in understanding the mechanisms that result in interface states and field induced hysteresis in GaAs MIS devices. The electrolytic bath generally consists of three basic components: a carboxylic acid, propylene glycol ($\text{CH}_3\text{CHOHCH}_2\text{OH}$) and water. To develop a model of the chemical reaction taking place during anodic oxidation of GaAs, we used

substitution of the anodizing acid as a variable parameter, and determined the stability and quality of the anodic oxide by measuring the capacitance versus voltage curve before and after annealing at 300 to 400°C. The C-V measurements were taken at various frequencies from 100 Hz to 10 kHz to determine the relative importance of slow and fast interface states. A detailed discussion of this work can be found in the unpublished thesis of D. G. Meyer²⁹ and only the highlights of his work are summarized here.

A well-known reaction which takes place in a solution containing a carboxylic acid and an alcohol is the esterification³⁰ of the acid and alcohol. In the process, the intermediary cations produced are of the following variety



where R and R' indicate the hydrocarbon group of the carboxylic acid and the alcohol, respectively. In our experiment, acids were picked according to the length of the hydrocarbon group R attached to the carboxyl group and the number of carboxyl groups per acid molecule. The acids used were citric, tartaric, oxalic, formic, and acetic. The final product of the esterification reaction is a alcohol, which through hydrogen ion exchange probably releases water:



This has the net effect of incorporating oxygen into the substrate, forming an oxide. Based on the model, it was expected that tartaric acid and citric acid would be most suitable because the reaction

intermediaries would be of the most stable type as the R in the intermediary cation is made of pure hydrocarbons. For the other acids, the reaction intermediaries would be more reactive as the R in the intermediary cations is made of either H or OH. Our experimental results on oxidation confirmed this observation. Oxides grown in tartaric or citric acid solutions were found atable and uniform, and no surface pitting was observed. On the other hand, with formic or acetic acid solutions, oxides could be grown only to approximately 400 Å thick. With oxalic acid solution, a light oxide could be grown only at high pH valued and surface pitting was found at low pH values. MIS structures were made on oxides grown in the tartaric solution and C-V measurements were taken before and after annealing in a forming gas. The lowest surface state density was found to be $1.6 \times 10^{12} \text{ cm}^{-2}$ per eV after 2 hours of annealing at 300°C, as compared to a value $0.6 \times 10^{12} \text{ cm}^{-2}$ per eV reported by Hasegawa et al.²⁸ and a value around 10^{11} cm^{-2} per eV found in silicon. This relatively high value of surface state density was probably due to unreacted bonds at the interface. The slow surface state density as determined from the hysteresis was estimated to have a lowest value about $2 \times 10^{11} \text{ cm}^{-2}$, probably due to incompletely oxidized Ga and As ions in the oxide. This preliminary study gave us some valuable insight to the oxidation mechanism and calls for our continued effort in search for a suitable insulator for III-V compounds.

Finally, we report our work on quaternary compounds. As mentioned earlier, the (GaIn)(AsP) system is important to optical fiber communications, and can be lattice-matched to InP. Another remarkable property is the flexibility in the atom arrangement provided by As and P atoms at the interface to minimize stress. Researchers at Nippon Electric Company³¹

have found that the quaternary (GaIn)(AsP) film is closely lattice matched to the InP substrate along the interface plane even at a composition away from the lattice-matching condition. What happens is that the lattice becomes tetragonal (instead of cubic) with the cell dimension perpendicular to the interface slightly elongated or contracted. Although the lattice is under stress, the stress is now minimized to an extent insufficient to generate dislocations. The long operating life observed in the quaternary laser may be attributed to this remarkable property. Since surface states play an important role in devices such as lasers and FET's where the thickness of the active layer or the conduction channel is very thin, the flexibility in atom arrangement at an interface may reduce the surface state density and thus improve the device characteristics. Recently we started LPE growth of InP films on InP substrates. As expected, the most severe problem we encountered is thermal decomposition of InP caused by high vapor pressure of phosphorus. Several approaches were undertaken to reduce thermal damage, including covering the wafer by the boat or by a dummy wafer, a technique first successful tried at Tokyo Institute of Technology.³² In the several latest runs, thermal damage seemed to have been substantially reduced. After melt-etch-back of the damaged surface, LPE layers of n and p InP were grown to form p-n junctions. When examined under Normaski interference microscope, the surface of the grown layers was shown to be reasonably smooth. Also reasonably good I-V characteristics were obtained. Our next task will be to further reduce the thermal damage and to grow LPE layers of (GaIn)(AsP) of good quality for device fabrications.

II. PERSONNEL

M.S. Thesis

G-J Chern, March 1979
D. G. Meyer, December 1977
R. B. Wood, September 1977

Ph.D. Thesis

C. Y. Chen (Ph.D. candidate, degree expected September 1980)
A. S. H. Liao (Ph.D. candidate, degree expected September 1980)
T. R. Ranganath, June 1979
K. M. Shams (Ph.D. candidate, deceased 1978)

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FIGURE CAPTIONS

Fig. 1. (a) The CJ laser structure,
(b) the emitted light spot,
(c) the near-field and far-field measurements
(d) the output spectrum and output versus injection current relation
(e) the output laser pulse and the injection current pulse

Fig. 2. (a) The LOC-DBR laser structure used in optical integration,
(b) the DBR laser output from the laser side compared with the detector output as a function of laser injection-current,
(c) the light output from the modulator side as a function of the modulator current,
(d) the spontaneous emission spectrum which shows strong interaction with the grating even below the laser threshold and the lasing spectrum of a high efficiency DBR laser,
(e) the temperature variation of the lasing wavelength,
(f) the output power from one facet versus injection current.

Fig. 3. Diagrams showing
(a) the schematic of an electrooptic modulator in the Mach-Zehnder interferometric configuration,
(b) the theoretical light intensity detected at the output arm as a function of applied voltage V , and
(c) the observed output light as a function of time for two voltage amplitudes, one smaller and the other larger than that required (4.8V) for peak modulation.

Fig. 4. Diagrams showing
(a) the schematic of a branch waveguide in contact with a Si mesa photodiode,
(b) the theoretical light intensity as a function of applied modulator voltage, and
(c) the photodiode voltage and the applied voltage as a function of time.

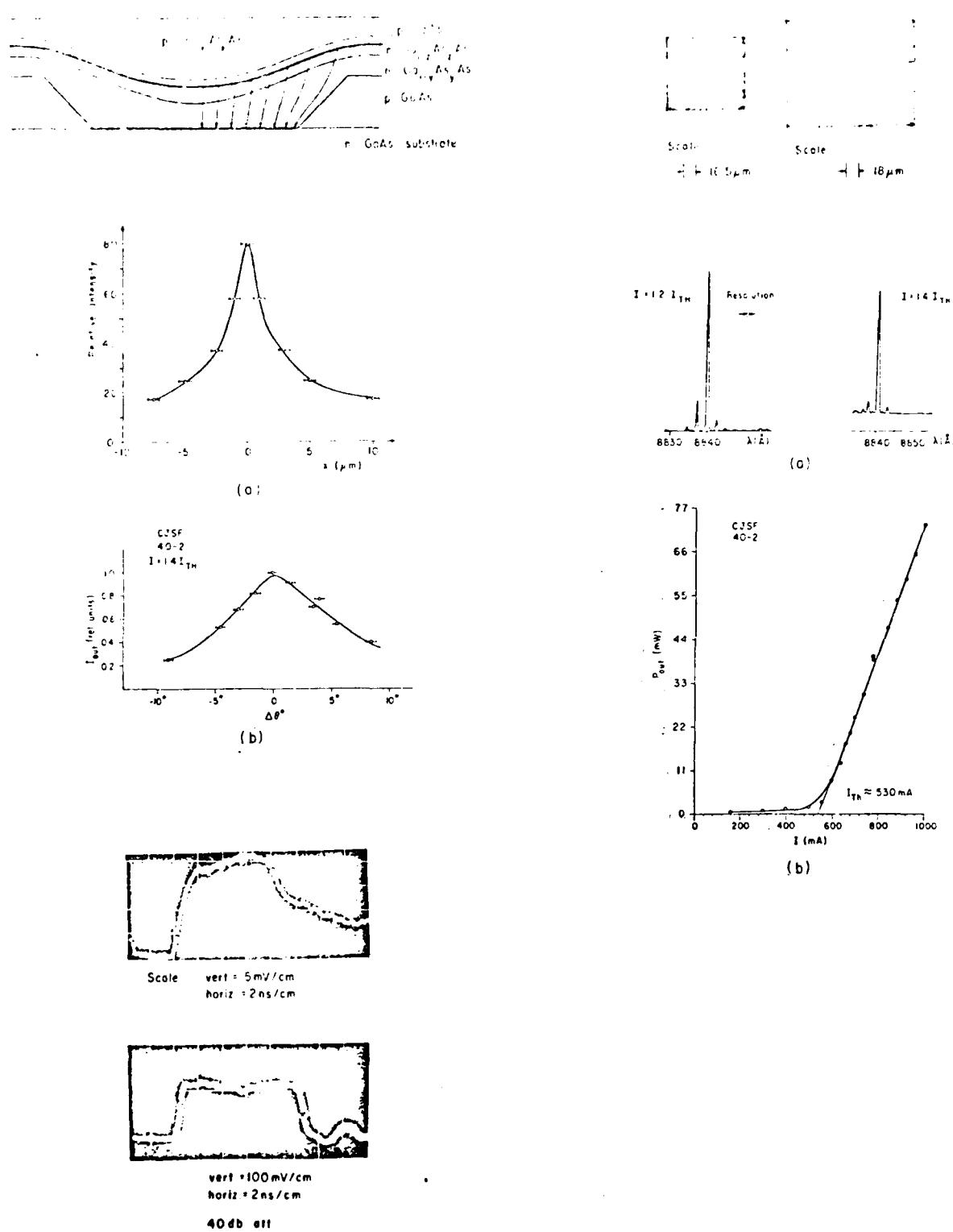
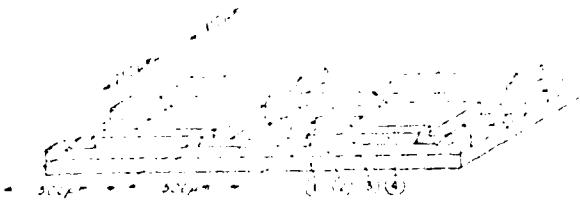


Figure 1

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Layer	Composition	Al content	thickness	doping
1	(Ga _{1-x} Al _x)As	x=0.23-0.25	2.4-3.6μm	n=1-2x10 ¹⁷ cm ⁻³
2	(Ga _{1-x} Al _x)As	x=0.05-0.1	0.6-2.5μm	n=1-2x10 ¹⁷ cm ⁻³
3	GaAs	0	0.25-0.4μm	undoped
4	(Ga _{1-x} Al _x)As	x=0.4-0.5	12-14μm	p>1x10 ¹⁹ cm ⁻³

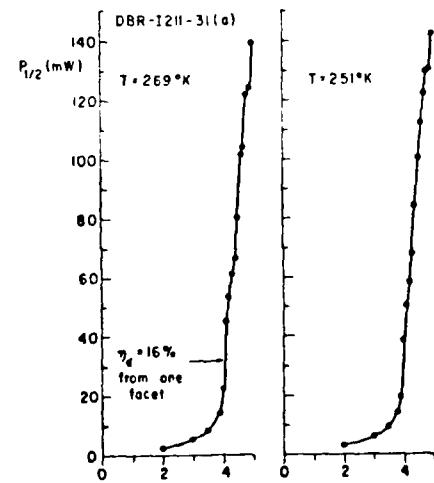
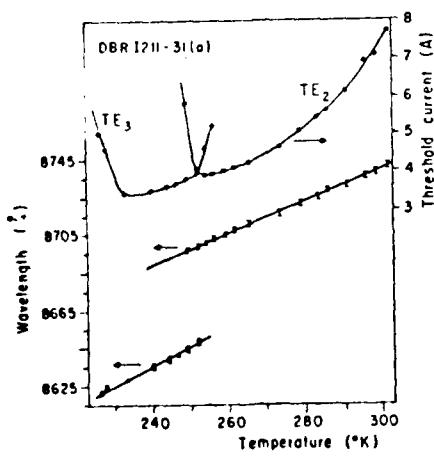
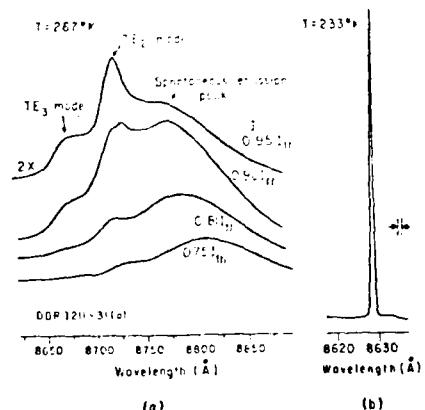
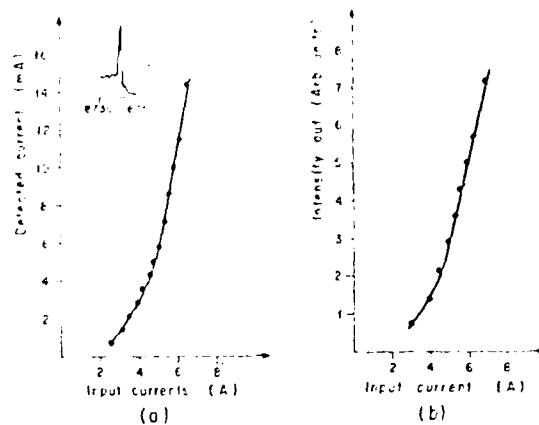
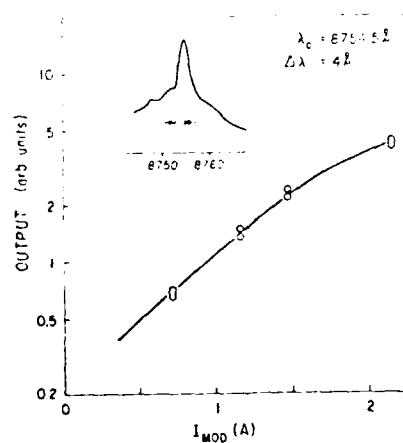
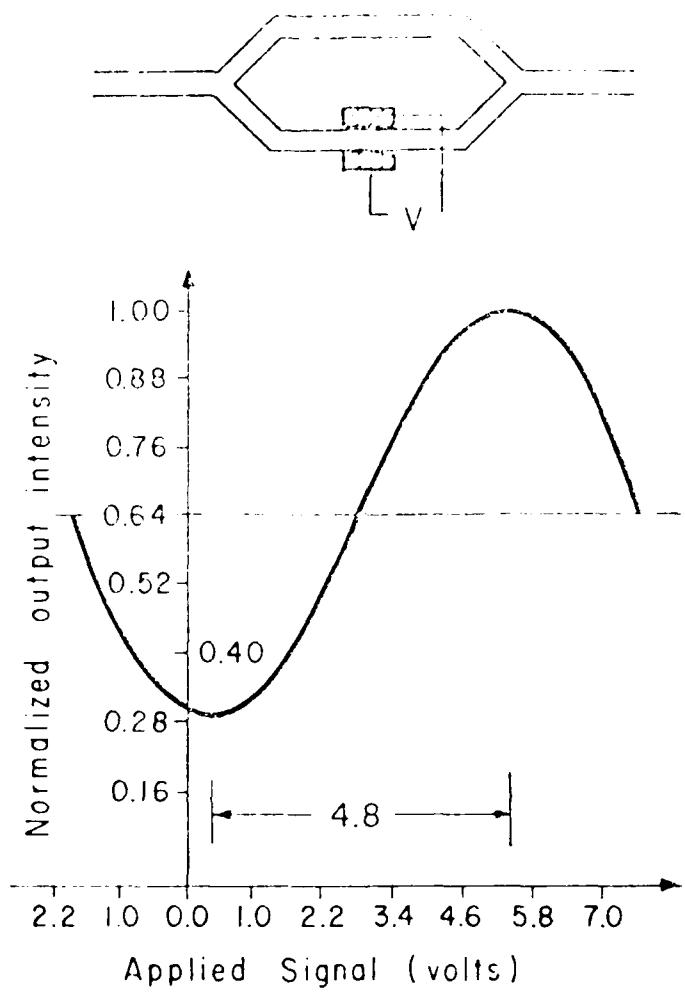
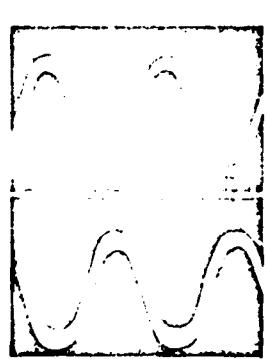


Figure 2



(a)

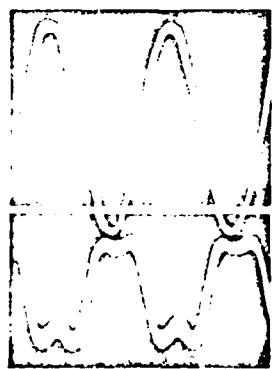


(b)

Applied signal
Scale: 2 volts/cm

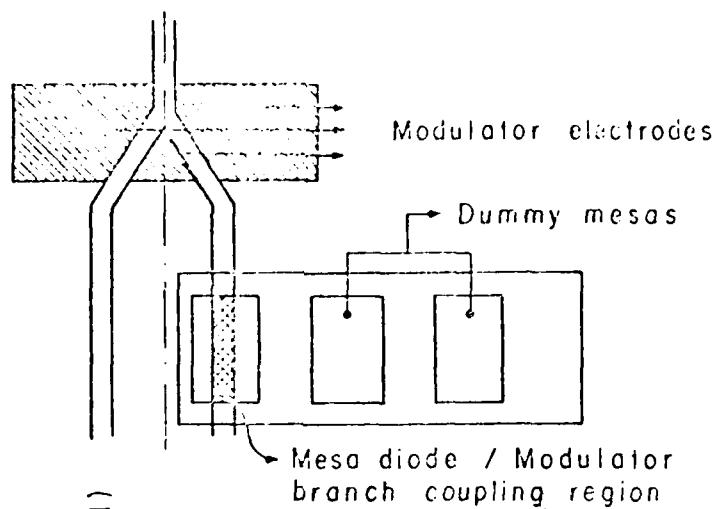
Zero light level

Detected output
Scale: 10 mV/cm

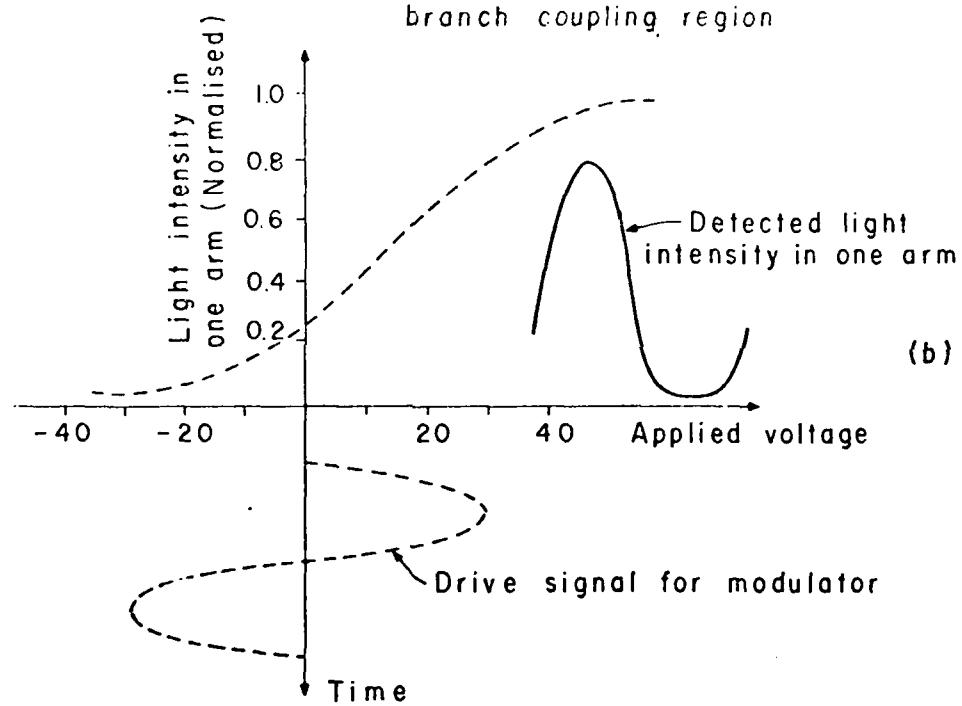


(c)

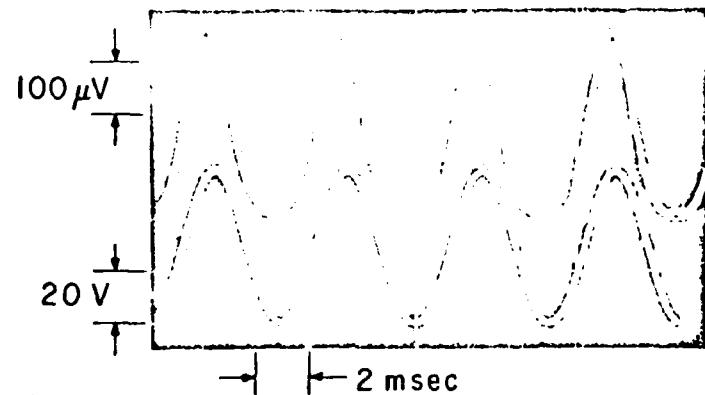
Figure 3



(a)



(b)



(c)

Figure 4

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